# Cosmic Rays, Clouds, and Climate

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It has been proposed that Earth's climate could be affected by changes in cloudiness caused by variations in the intensity of galactic cosmic rays in the atmosphere. This proposal stems from an observed correlation between cosmic ray intensity and Earth's average cloud cover over the course of one solar cycle. Some scientists question the reliability of the observations, whereas others, who accept them as reliable, suggest that the correlation may be caused by other physical phenomena with decadal periods or by a response to volcanic activity or El Niño. Nevertheless, the observation has raised the intriguing possibility that a cosmic ray–cloud interaction may help explain how a relatively small change in solar output can produce much larger changes in Earth's climate. Physical mechanisms have been proposed to explain how cosmic rays could affect clouds, but they need to be investigated further if the observation is to become more than just another correlation among geophysical variables.

The correlation between cosmic rays and Earth's cloud cover over a solar cycle, first reported by Svensmark and Friis-Christensen in 1997 (*1*), was hailed by some as the missing piece in the puzzle of understanding how the Sun could influence climate change. The intensity of cosmic rays varies globally by about 15% over a solar cycle because of changes in the strength of the solar wind, which carries a weak magnetic field into the heliosphere, partially shielding Earth from low-energy galactic charged particles. Although long suspected of having some influence on atmospheric processes (*2*, *3*), the correlation between cosmic rays and global cloudiness was, to some, the clearest indication that such a link might exist.

Changes in cloud cover are important because clouds exert a strong control over Earth's radiative balance. Since the original observation (*1*), improved satellite data have become available and the cosmic ray–cloud effect seems to be present in low-altitude clouds (*4*) (Fig. 1). Because low clouds exert a large net cooling effect on the climate, this determines the sign of the possible cosmic ray–cloud effect: More cosmic rays are associated with more low clouds and lower temperatures. The observed variation of low clouds by about 1.7% absolute corresponds to a change in Earth's radiation budget of about 1 $Wm^{-2}$ between solar maximum and minimum. This change in energy input to the lower atmosphere is highly significant when compared, for example, with the estimated radiative forcing of 1.4 $Wm^{-2}$ from anthropogenic $CO_2$ emissions.

If the solar cycle variation were the end of the story, then the cosmic ray–cloud effect would be of marginal interest because the large thermal inertia of the oceans would dampen the global temperature changes to less than 0.1 K. However, the cosmic ray intensity has varied in the past on centennial and millennial time scales (in the latter case by as much as a factor of 3 to 4) as a result of stochastic changes of solar magnetic activity and changes of the geomagnetic field. The cosmic ray intensity, as reconstructed from $^{10}$Be concentrations in ice cores (*5*), declined by about 15% during the 20th century owing to an increase in the solar open magnetic flux by more than a factor of 2 (*6*) (Fig. 2). This 100-year change in intensity is about the same magnitude as the observed change over the last solar cycle (Fig. 1). If the cosmic ray–cloud effect is real, then these long-term changes of cosmic ray intensity could substantially influence climate, bringing additional uncertainties to climate-change projections. Such possibilities make this a fiercely debated geophysical phenomenon, and hence all the more important to understand the cause of the cloudiness variations.

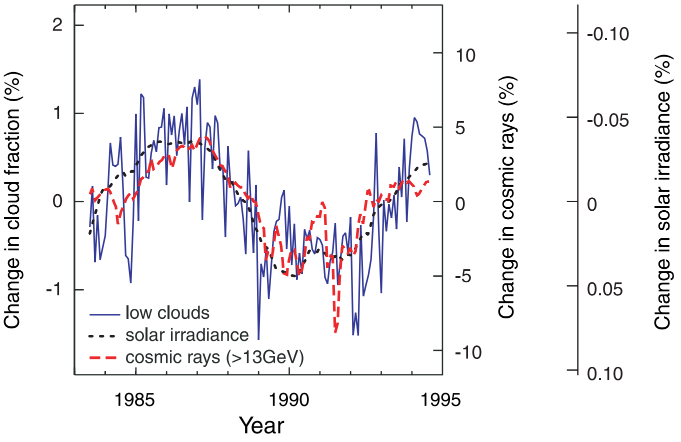

**Fig. 1.** Variation of low-altitude cloud cover, cosmic rays, and total solar irradiance between 1984 and 1994. The cosmic ray intensity is from Huancayo observatory, Hawaii. [Adapted from (*4*)]

The observation of a correlation between cosmic rays and cloudiness comes after two centuries of effort to determine the influence of solar variability on Earth's weather. In 1801, the Astronomer Royal, William Herschel, effectively launched the field of solar variability influences on weather by noticing an anticorrelation between the price of wheat and the number of visible sunspots (*7*). Since then, numerous studies have shown additional correlations between solar and other geophysical variables (*8*). These include an apparent solar influence (on various time scales) on temperatures, thunderstorm frequency, tropopause heights, atmospheric circulation, and occurrence of drought, to name but a few. Whereas many of the studies have been based on correlations with the sunspot number, the most persuasive evidence for a solar effect on climate change has emerged from recent palaeoclimatic studies based on the cosmic ray archives provided by the $^{14}$C records in tree rings and $^{10}$Be concentrations in ice cores (*9*, *10*). Of course, the cosmic ray–climate correlations observed in these studies cannot in general distinguish between a direct cosmic ray effect on the climate and a solar irradiance effect, for which the cosmic rays act as a proxy.

Three principal mechanisms have been suggested to link solar variability with changes in Earth's weather. The first, originally proposed by Herschel, is that changes in total solar irradiance provide a variable heat input to the lower atmosphere. Relatively recent measurements of the solar irradiance have shown the Sun's output to vary by about 0.1% on decadal time scales (*11*, *12*), which is sufficient to account for a solar-induced global average temperature change of about 0.1 K (*13*). The second suggested forcing mechanism is through the solar ultraviolet radiation, which varies by several percent

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over a solar cycle. The hypothesis is that changes in the ozone concentrations and heating of the stratosphere, where the ultraviolet radiation is absorbed, couple dynamically to the lower atmosphere (*14*). The third suggested forcing mechanism is through the effect of galactic cosmic rays on the weather (*3*, *15*), involving cloud processes such as condensation nucleus abundances (*16*), thunderstorm electrification and thermodynamics (*17*), or ice formation in cyclones (*18*, *19*). It is this third possibility that forms the subject of this article (*20*).

Correlations are rife in the field of solar variability and weather because the complexity of the climate system means that they are not easy to explain (or explain away) by using mechanistic models. Indeed, history has witnessed numerous apparent solar cycle effects on the climate that have persisted for some decades and then ceased to be apparent in the data (*8*). Is the cosmic ray–cloud correlation the one that will finally lead us to an acceptable mechanism?

## Cosmic Rays in the Atmosphere

Cosmic rays are composed predominantly of high-energy protons generated by supernovae and other energetic sources in our Galaxy. On entering the heliosphere, charged cosmic rays are deflected by the inhomogeneous magnetic fields of the solar wind, and by Earth's dipole field. Over the solar cycle, the variation of cosmic ray intensity at the top of the atmosphere is about 15%, globally averaged, and ranges from about 5% near the geomagnetic equator to 50% at the poles. Showers of secondary particles are produced in the upper troposphere, and muons dominate the cosmic ray intensity below about 6-km altitude.

The energy input from cosmic rays is tiny—about one-billionth of the solar irradiance, or roughly the same as that of starlight. However, as the dominant source of penetrating ionizing particle radiation, they have a profound effect on many atmospheric processes. They generate, for example, light radioisotopes such as $^{14}$C and $^{10}$Be by interactions with air nuclei, which provides the basis for carbon dating as well as reconstructing past changes of cosmic ray intensity. There are also at least two major effects of cosmic rays on the electrical properties of the atmosphere: Cosmic rays provide the sole source of ions away from terrestrial sources of radioisotopes such as radon, and cosmic ray variations directly influence the global atmospheric electric circuit. Cosmic ray ionization maintains the atmosphere as a very dilute electrically conducting plasma, allowing a continuous electrical current to pass from the ionosphere to Earth's surface.

The cosmic ray ionization rate varies between about 2 ion pairs cm$^{-3}$ s$^{-1}$ close to Earth's surface and 40 ion pairs cm$^{-3}$ s$^{-1}$ at the top of the troposphere. The positive ions and free electrons created by cosmic rays rapidly interact with molecules in the atmosphere and are converted to complex positive and negative cluster ions termed "small ions." Small ions are lost by various mechanisms such as ion-ion recombination, ion-aerosol attachment and, in clouds, ion-droplet attachment. The equilibrium ion concentration, of both signs, in clean air is about 500 to 3000 cm$^{-3}$, depending on altitude and latitude. Lower ion concentrations are found in polluted air as a result of ion-aerosol attachment.

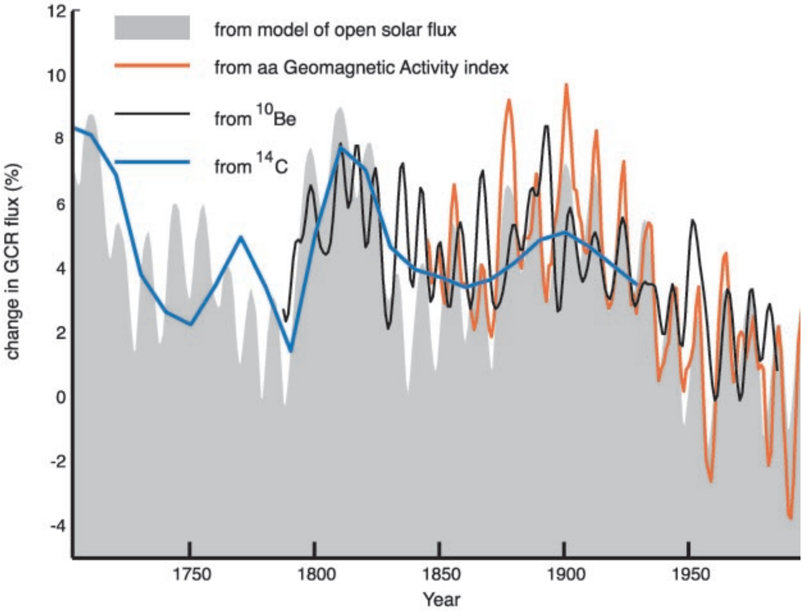

**Fig. 2.** Change in cosmic ray intensity between 1700 and the present day from four independent proxies. Intensities have been scaled to the 13-GeV cosmic ray data from Huancayo, Hawaii, and then normalized to the 1990–2001 mean. The plot shows deviations from this mean. [Adapted from figure 12 and data in (*56*)]

## Cloud and Cosmic Ray Observations

Following the original observation of a cosmic ray–cloud correlation in 1997 (*1*), several investigators pointed out important limitations in the satellite cloud data and its analysis (*21*, *22*). These limitations have largely been addressed with the release of the D2 data set of the International Satellite Cloud Climatology Project (ISCCP) (*23*), which now constitutes the best continuous satellite cloud data set. The global-average cloud coverage derived from infrared measurements correlates with the cosmic ray intensity and solar radiation for low clouds (altitudes of less than about 3 km) but not for higher-level clouds (*4*, *24*) (Fig. 1). However, there is still considerable uncertainty as to whether these or other cloud data show a long-term significant correlation with cosmic ray intensity (*25*, *26*)

Correlations between cloud cover and sudden decreases in cosmic rays on the time scale of days have also been reported (*27*), and appear to be dominated by changes in cirrus clouds. These temporary decreases, known as Forbush events, are due to large solar-mass ejections and suggest the possibility of attributing cloud variations to cosmic rays. However, the cloudiness variations have been detected only in visual cloud observations. These are spatially limited and the statistics are, as yet, rather poor.

Observations of cosmic ray–cloud correlations are not the only motivation for studying ion-aerosol-cloud processes further. The study of climate change itself is not rooted in the observational evidence of a warming. Rather, scientists began studying climate change based primarily on the observation that CO$_2$ was rising steeply and the notion, based on simple radiative-forcing arguments, that the atmospheric CO$_2$ burden could not continue to rise without producing some effect on climate. Cosmic rays and clouds are no different; one point of view is that it is inconceivable that the lower atmosphere can be globally bombarded by ionizing radiation without producing an effect on the climate system. This expectation of an effect arises because ions influence a host of individually well-understood or plausible aerosol and cloud processes. In short, even the breakdown of the cosmic ray–cloud correlation would not disprove any physical connection; until we establish the physical interactions, we cannot know what to expect in the atmospheric observations.

## Physical Processes

The occurrence of clouds throughout most of the atmosphere is well predicted by meteorological parameters such as humidity, temperature, and atmospheric dynamics. However, many properties of clouds, such as their reflectivity and lifetime (and therefore coverage), are influenced in subtle but important ways by a series of complex processes occurring at the level of individual aerosol and cloud particles—so-called microphysical processes. Indeed, a major focus of current cloud research—the effect of pollution on clouds—involves quantifying a small perturbation to global cloud properties induced by changes in aerosol properties (*28*). A mechanism linking cosmic rays and clouds could operate directly through the influence of ions on such microphysical processes.

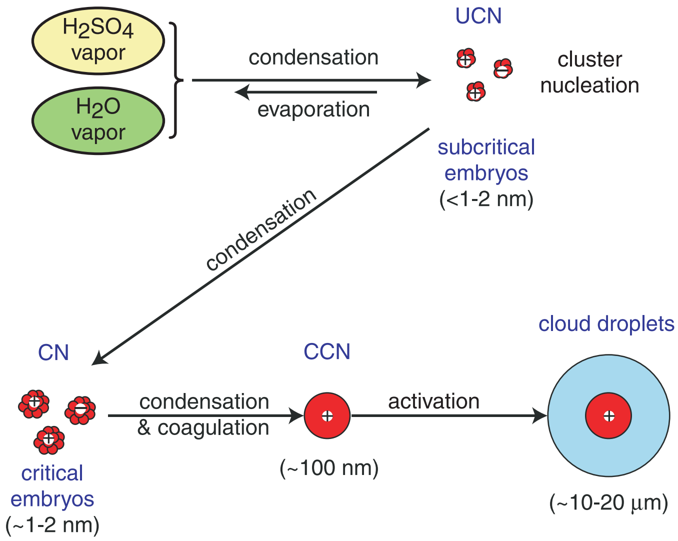

**Fig. 3.** An "ion-aerosol clear-air" mechanism proposed to link variations in cosmic ray intensity with cloudiness. The diagram shows the ion-catalyzed nucleation of new ultrafine condensation nuclei (UCN) from trace condensable vapors in the atmosphere, which may then grow into new cloud condensation nuclei (CCN).

A key quantity is the cloud droplet number concentration, which is determined by the cloud condensation nuclei (CCN) population—that fraction of the aerosol with sufficient diameter, typically greater than about 0.1 µm, to act as nuclei for cloud droplet formation (*29*). The droplet number concentration controls the cloud reflectivity and the efficiency of rainfall generation in extensive low-level stratus clouds. Rainfall is an important controlling factor in cloud lifetime, and hence in the average cloudiness of a region. Another important quantity is the formation of ice in a cloud. Ice particles grow rapidly and induce rainfall because liquid clouds are highly supersaturated with respect to ice. Ice formation also affects the thermodynamic structure of a cloud, which is also likely to affect cloud coverage, although the connection is complex. Two mechanisms by which cosmic rays may affect cloud droplet number concentrations or ice particles are described below. We call these two mechanisms the ion-aerosol clear-air mechanism and the ion-aerosol near-cloud mechanism.

*Ion-aerosol clear-air mechanism.* The ion-aerosol clear-air mechanism (Fig. 3) is based on the expectation that the presence of ions enhances the birth and early growth of aerosol particles in the atmosphere. A fraction of these may eventually grow into CCN.

An important source of new aerosol particles in the atmosphere is the nucleation of ultrafine condensation nuclei from trace condensable vapors such as sulfuric acid. Despite intensive research over several decades, the sources of the ubiquitous background of ultrafine aerosols in the troposphere have not been conclusively identified. In the case of binary sulfuric acid–water nucleation, the nucleation rates predicted by classical theory are far lower than the experimentally observed rates. Two mechanisms that have been proposed to explain this discrepancy are ternary nucleation involving ammonia (*30*, *31*) and ion-induced nucleation (*32*). Recent modeling work (*33*, *34*) suggests that the presence of charge serves to lower the nucleation barrier and stabilize the embryonic particles. This allows nucleation to take place at lower ambient vapor concentrations than in a nonionized atmosphere. These models indicate that the nucleation rate of fresh aerosol particles in clean regions of the atmosphere, such as the marine boundary layer, is frequently limited by the ion production rate from cosmic rays.

How does the CCN number depend on the rate of formation of new particles, and what effect might a small variation of ionization rate have on CCN? Aerosol particles and trace vapors are continually being scavenged from the atmosphere by rainfall. Under such conditions, there is rarely sufficient time for a large CCN population to form, so the rate at which new particles are produced does influence the CCN number, albeit in a far from straightforward way. The ability of newly formed aerosol particles to grow to CCN sizes depends on the competition between condensation growth (which preserves particle number concentrations) and processes that reduce particle concentrations, such as coagulation, surface deposition, and scavenging in clouds. Besides enhancing nucleation, charged aerosol particles resulting from cosmic ray ionization can also grow more quickly than uncharged particles owing to the enhanced condensation rate of polar molecules—calculations suggest by at least a factor of 2 in growing from 1 to 5 nm (*33*). Because the coagulation loss rate of 5-nm-radius particles is 1/20th of that of 1-nm-radius particles (*35*), charge-enhanced growth is an important factor in determining the critical early survival rate of new aerosol particles.

Model calculations (*33*, *34*, *36*) suggest that a 20% variation in the ionization rate in the lower atmosphere could lead to a change in the concentration of 3- to 10-nm-diameter aerosols of about 5 to 10%. Some of these particles will certainly eventually contribute to the CCN population, but the fraction of CCN originating from cosmic ray ionization will depend on many factors, including availability of condensable gases, direct sources of CCN, and cloud processing. Interestingly, the model results also suggest that modulation of aerosol concentrations will be greatest in the lowest part of the atmosphere, where the ionization rate is a limiting factor in new particle formation, and not at higher altitudes, where the cosmic ray intensity is greater (*33*, *36*). This theoretical result may help us to understand why the cosmic ray–cloud correlation is apparent only in low-altitude clouds (*4*).

What might be the net effect on clouds of changes in cosmic ray intensity? Assuming that an increase in cosmic ray intensity leads to an increase in CCN abundance, the situation becomes similar to the so-called aerosol indirect effect (Table 1)—a negative radiative forcing of the climate system caused by changes in cloud properties in response to aerosol pollution. At the simplest level, human-induced increases in aerosol number concentrations lead to increases in cloud droplet number concentrations in polluted clouds, as well as a reduction in droplet sizes (because the cloud liquid water content is essentially determined by the cloud dynamics). The consequences of increased droplet concentrations are twofold: an increase in cloud reflectivity and a suppression of rainfall, and therefore an increase in cloud lifetime. These effects have been observed in the atmosphere (*28*, *37*, *38*).

The proposed cosmic ray effect and the indirect effect of aerosols on clouds are similar in that both are driven by changes in aerosol number. But there are important differences. First, the aerosol indirect effect is driven by changes in aerosol mass caused by changes in the supply of condensable vapors (primarily $SO_2$), whereas the cosmic ray–cloud effect is driven only by changes in the rates of certain microphysical processes. Second, the cosmic ray effect has the potential to induce small changes in aerosol number on a global scale, whereas pollution tends to increase aerosol concentrations greatly in limited regions. Third, pollution effects are strongest near inhabited regions, whereas cosmic ray effects are likely to be most effective in regions of low aerosol concentration, such as clean regions over oceans.

There are relatively sparse experimental data on the effect of ions on new particle formation (*39*). Laboratory observations have shown that ions can act as sources for new particles (*40*, *41*), and recent aircraft measurements have found evidence for cosmic ray–induced aerosol formation in the upper troposphere (*42*). In addition, ions produced in aircraft condensation trails have been shown to act as sites for the formation of new particles (*43*). Furthermore, ions can account for some bursts of new aerosol in the marine atmosphere (*44*), but particle concentrations in other cases (*45*, *46*) appear to be too large to be caused by cosmic rays. Although suggestive, these observations are incomplete and insufficient to establish a net overall effect of ionization on aerosol concentrations in the atmosphere. Present estimates of the magnitude of the effect are therefore based on model simulations.

*Ion-aerosol near-cloud mechanism.* The ion-aerosol near-cloud mechanism (Fig. 4) is less well understood. It hinges on the fact that the aerosol electrical charge—and how this charge varies with changes in the ionization rate—is very different near clouds than it is in clear air. The proposal stems from observations of perturbations in the fair-weather electric field and vertical conduction current caused by the presence of a cloud layer. These perturbations cause the upper part of a thin stratiform cloud to become more positively charged than the clear air above it, with a gradual return to quiescent values about 200 m above the cloud (*47*) (Fig. 4). Perturbations in aerosol charge, although of smaller magnitude, also exist around layers of aerosol and at the top of the polluted boundary layer (*48*).

Within the cloud, small ions are very efficiently removed by cloud droplets, and the electrical conductivity is sharply reduced from the clear-air values. This difference between the conductivities of clear air and of clouds causes a layer of net unipolar charge (a space charge) to accumulate at the cloud-air boundaries. Equilibrium droplet charges at cloud boundaries are consequently quite large (*48*)—about 100 electronic charges (*e*)—and the unipolar charge and low-conductivity environment around the cloud prevent the rapid neutralization of such droplets. Aerosol particles in this region are also relatively highly charged. The space charge increases the electric field in the low-conductivity region within the cloud, thereby restoring the equilibrium vertical conduction current. Thus, although electrical effects are much weaker in stratiform clouds than in thunderstorms, they are certainly present and, as we discuss below, the electric fields and charge densities are modulated by cosmic rays.

Tinsley and co-workers (*49*, *50*) have suggested that electrification enhances aerosol efficacy as ice-forming nuclei. There is some theoretical and experimental support for this because aerosol removal by water drops (scavenging) is substantially increased if the aerosols are charged. Ice nucleation may therefore be increased if the scavenged charged particles are also effective ice contact nuclei (*51*). Calculations show that the scavenging rate increases rapidly with the aerosol charge, due to image charges (*51*, *52*), which are always attractive and dominate close to the droplet, regardless of the relative sign of the aerosol and droplet charges. Increases in the scavenging rates depend on both the presence of the highly charged aerosols and their transport into the cloud. As yet, there are no measurements of the in-cloud and near-cloud abundances of such highly charged aerosols. One possible source is the evaporation of highly charged droplets (*50*) at cloud boundaries. Charge is not lost by droplet evaporation, and so highly charged aerosol particles are also created at cloud boundaries, although they will eventually be discharged once they are mixed into a bipolar-ion environment.

What might be the net effect of changes in cosmic ray intensity on the charging of aerosol particles at cloud boundaries? First, the local ionization rate is proportional to cosmic ray intensity, so the rate at which ions are supplied to the space charge is directly affected. Second, the ambient atmospheric electric field, and hence the drift velocity of ions into the cloud boundaries, is also modulated by cosmic rays (*53*). [A related long-term decrease of the atmospheric electric field is apparent during the past century (*54*).] Changes in cosmic ray intensity are therefore expected to modulate the magnitude of the aerosol charges around clouds, with possible consequences for the microphysical processes involving aerosol and droplets. However, although the above processes are physically plausible, there are no direct observations quantifying the modulation of charge density near clouds with changes in cosmic rays.

How might clouds respond to changes in cosmic ray intensity through these microphysical connections? We think it is premature to say with any certainty. If the electrically enhanced ice-nucleation mechanism is widespread in natural clouds, then a decrease of cosmic rays could lead to a decrease of ice-particle formation and hence a decrease in rainfall (which would produce a change in cloudiness opposite to that observed). However, the effect on cloud structure of changes in latent heat release would also need to be considered, and this may reverse the sign of the effect. The factors that control the abundance of ice nuclei in the atmosphere, and how ice clouds develop, are at the frontier of cloud physics research, and many uncertainties remain. Other than the proposal of Tinsley and Heelis (*49*) and recent related work, the microphysical effects of high aerosol and droplet charges at the boundaries of nonthunderstorm clouds have not been considered.

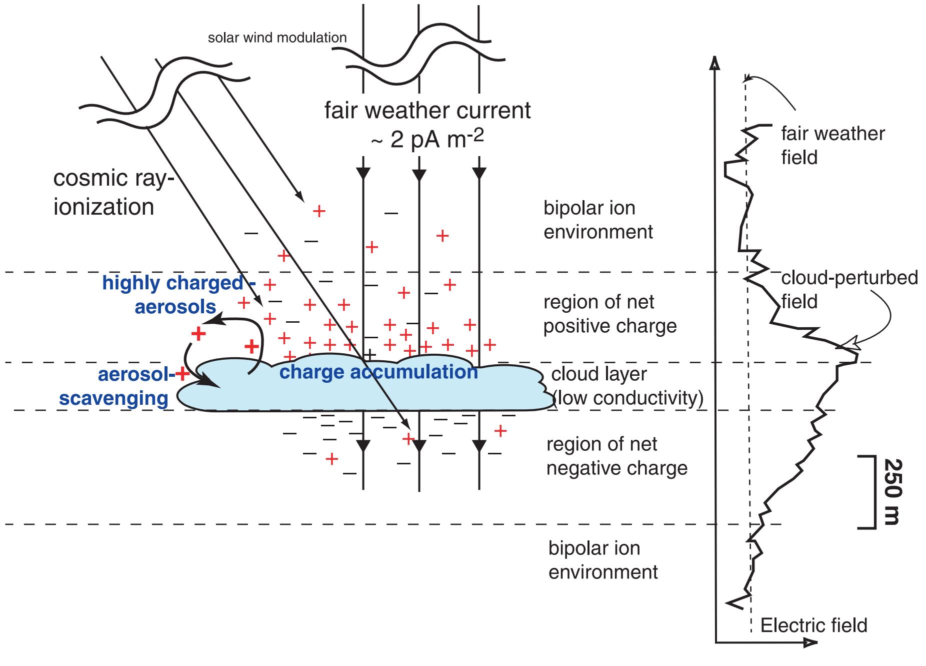

**Fig. 4.** An "ion-aerosol near-cloud" mechanism. The diagram shows the development of highly charged aerosols at cloud boundaries, which may then migrate within clouds and possibly enhance the formation of ice particles. The electric-field profile on the right side is taken from observations (*48*). The vertical scale is also shown.

The near-cloud mechanism may include several processes operating at once, and the direction of the effect (greater or lesser cloudiness) in response to cosmic ray changes cannot be predicted with any confidence.

Finally, it is useful to contrast the important differences between the ion-aerosol clear-air and near-cloud mechanisms with respect to changes in the cosmic ray intensity. In the former case, the aerosol charges are small—typically a few *e*—and insensitive to cosmic ray intensity. In this mechanism, the sensitivity to the ion-pair production rate arises because each newly created ion is capable of seeding a new aerosol particle. In the latter case, the aerosol charges are large—around 100*e*—and the magnitude of the charge depends directly on the cosmic ray intensity through its effects both on ion-pair concentrations and on the vertical electric field (ion drift velocity). However, little is known about the effect of charged aerosols on cloud microphysics, and how it varies with the magnitude or perhaps sign of the charge; and even less is known quantitatively about the response to variations of cosmic ray intensity.

**Table 1.** Comparison of the aerosol indirect effect on climate (*28*) and the cosmic ray–cloud effect.

| | Aerosol indirect effect | Cosmic ray–cloud effect |
|---|---|---|
| Cause | Change in total aerosol loading or condensable vapor loading | Changes in rates of some microphysical processes attributable to ions |
| Effect on clouds | Rainfall suppression, increases in cloud lifetimes, cloud cover, and reflectivity | Same, but effect of some proposed mechanisms unknown |
| Extent of effect | Large effect in spatially limited, polluted regions of the atmosphere | Potentially global-scale, but possibly favoring a clean atmosphere |
| Implications | Global mean radiative cooling comparable to greenhouse gas–induced warming | Possible sizable modification of global energy balance on decadal, centennial, and millennial time scales |
| Level of scientific understanding | Very low (*28*), but most processes probably identified | Even lower, with some processes proposed but untested |

## Conclusions

The subject of Sun-weather relations is founded on correlations between solar and atmospheric variables, but to make further progress now requires investigations at the mechanistic level. The observation of a correlation between cosmic ray intensity and cloudiness offers an opportunity for a mechanistic understanding in terms of ion-aerosol-cloud interactions. The known behavior of ions in the atmosphere suggests that variations in their production rate by cosmic rays will impact aerosol and cloud processes to some extent, but it remains to be established whether such variations could lead to detectable changes in cloud properties.

The aim of mechanistic investigations is to go beyond mere association of observed variables to a situation where predictions can be made and tested. However, in this respect, the cosmic ray–cloud problem offers an even greater challenge than other aerosol-cloud interaction problems at the frontier of current research. Demonstrating overall cause and effect, beginning with changes in ionization rate and ending with observations of perturbed clouds, will present a challenge. The natural variability of clouds at a single location due to meteorology, aerosol abundance, and composition changes will make it difficult to detect a few percent modulation caused by ionization. As a result, the signal of a cosmic ray influence, if it exists, may show up only in long-term and large-area averages, such as those indicated in Fig. 1. However, such averages open up the possibility that numerous other processes could contribute to the observed variability, complicating efforts to discern a clear regional pattern associated with cosmic rays.

It will also be difficult to separate solar and cosmic ray effects, both of which vary in a similar way. Geomagnetic field variations could in principle untangle this ambiguity because they affect cosmic rays but not solar irradiance, but these variations occur on much longer time scales than the solar variations.

Nevertheless, recent progress has been made in understanding the physical processes involved in the cosmic ray–cloud effect, upon which further studies can build. Laboratory work under carefully controlled conditions is needed to study the microphysics of ion-aerosol-cloud interactions and to measure poorly constrained parameters in the present models. Field studies of aerosol nucleation bursts are needed that include measurements of ion mobility and, if possible, ion chemical composition to allow quantitative comparisons with models and the laboratory measurements. Improved observations of stratiform clouds are required, especially concerning the electrical conditions and aerosol charges at the cloud boundaries and within clouds. More realistic aerosol and cloud models are required that incorporate the ion effects measured in the laboratory and field. Combined efforts in this direction may quite quickly be able to establish whether cause and effect is plausible, and to quantify the physical processes involved in the interactions of cosmic rays with clouds.

### References and notes

1. H. Svensmark, E. Friis-Christensen, *J. Atmos. Solar Terr. Phys.* **59**, 1225 (1997).
2. C. T. R. Wilson, *Proc. R. Soc. London* **64**, 127 (1899).
3. E. P. Ney, *Nature* **183**, 415 (1959).
4. N. Marsh, H. Svensmark, *Phys. Rev. Lett.* **85**, 5004 (2000).
5. J. Beer *et al.*, *Nature* **347**, 164 (1990).
6. M. Lockwood, R. Stamper, M. N. Wild, *Nature* **399**, 437 (1999).
7. W. Herschel, *Philos. Trans. R. Soc. London* **265**, 354 (1801).
8. D. V. Hoyt, K. T. Schatten, *The Role of the Sun in Climate Change* (Oxford Univ. Press, Oxford, 1997).
9. J. Beer, *Space Sci. Rev.* **94**, 53 (2000).
10. G. C. Bond *et al.*, *Science* **294**, 2130 (2001).
11. C. Fröhlich, J. Lean, *Proc. Int. Astron. Union Symp.* **185**, 89 (1998).
12. ———, *Geophys. Res. Lett.* **25**, 4377 (1998).
13. T. M. L. Wigley, S. C. B. Raper, *Geophys. Res. Lett.* **17**, 2169 (1990).
14. J. D. Haigh, *Science* **272**, 981 (1996).
15. J. M. Wilcox *et al.*, *J. Atmos. Sci.* **31**, 581 (1974).
16. R. E Dickinson, *Bull. Am. Meteorol. Soc.* **56**, 1240 (1975).
17. R. Markson, M. Muir, *Science* **206**, 979 (1980).
18. B. W. Tinsley, G. W. Den, *J. Geophys. Res.* **96**, 22283 (1991).
19. B. W. Tinsley, *J. Geophys. Res.* **101**, 29701 (1996).
20. Further information on the influence of cosmic rays on the atmosphere can be found in *Proceedings of the Workshop on Ion-Aerosol-Cloud Interactions*, J. Kirkby, Ed. (CERN, Geneva, CERN 2001-007, 2001).
21. S. C. Kernthaler, R. Toumi, J. D. Haigh, *Geophys. Res. Lett.* **26**, 863 (1999).
22. T. B. Jorgensen, A. W. Hansen, *J. Atmos. Solar Terr. Phys.* **62**, 73 (2000).
23. W. B. Rossow, R. A. Schiffer, *Bull. Am. Meteorol. Soc.* **72**, 2 (1991).
24. J. E. Kristjánsson, J. Kristiansen, *J. Geophys. Res.* **105**, 11851 (2000).
25. N. Marsh, H. Svensmark, *J. Geophys. Res.*, in press (10.1029/2002JD001264).
26. B. Sun, R. S. Bradley, *J. Geophys. Res.* **107**, D14 (2002); published online 27 July 2002 (10.1029/2001JD000560).
27. M. I. Pudovkin, S. V. Veretenenko, *J. Atmos. Terr. Phys.* **75**, 1349 (1995).
28. J. E. Penner *et al.*, in *Climate Change 2001: The Scientific Basis*, J. T. Houghton *et al.*, Eds. (Cambridge Univ. Press, Cambridge, 2001), pp. 291–348.
29. The CCN size is not fixed, but depends on the chemical composition of the aerosol, the CCN size distribution, and the dynamics of the cloud involved.
30. P. Korhonen *et al.*, *J. Geophys. Res.* **104**, 26349 (1999).
31. M. Kulmala, L. Pirjola, J. M. Mäkelä, *Nature* **404**, 66 (2000).
32. F. Raes, A. Janssens, R. Van Dingenen, *J. Aerosol Sci.* **17**, 466 (1986).
33. F. Yu, R. P. Turco, *J. Geophys. Res.* **106**, 4797 (2001).
34. R. P. Turco, F. Q. Yu, J. X. Zhao, *J. Air Waste Manage.* **50,** 902 (2000).
35. This calculation refers to Brownian coagulation with a 1-μm-diameter particle representative of a typical background tropospheric aerosol population.
36. F. Yu, *J. Geophys. Res.* **107**, A7 (2002); published online 19 July 2002 (10.1029/2001JA0D0248).
37. J.-L. Brenguier *et al.*, *J. Atmos. Sci.* **57**, 803 (2000).
38. D. Rosenfield, *Science* **287**, 1793 (2000).
39. R. G. Harrison, K. L. Aplin, *J. Atmos. Solar Terr. Phys.* **63**, 1811 (2001).
40. J. Bricard, F. Billard, G. Madelaine, *J. Geophys. Res.* **73**, 4487 (1968).
41. K. G. Vohra, M. C. Subba Ramu, T. S. Muraleedharan, *Atmos. Environ.* **18**, 1653 (1984).

42. S. Eichkorn, S. Wilhelm, H. Aufmhoff, K.-H. Wohlfrom, F. Arnold, *Geophys. Res. Lett.* **29**, 43-1 (2002); published online 27 July 2002 (10.1029/2002GL015044).
43. K.-H. Wohlfrom, S. Eichkorn, F. Arnold, P. Schulte, *Geophys. Res. Lett.* **27**, 3853 (2000).
44. F. Yu, R. P. Turco, *Geophys. Res. Lett.* **27**, 883 (2000).
45. C. D. O'Dowd *et al.*, *Geophys. Res. Lett.* **26**, 1707 (1999).
46. J. M. Makela *et al.*, *Geophys. Res. Lett.* **24**, 1219 (1997).
47. The depth of the space-charge layer depends on the transport of ions into and out of the layer by the drift current and by turbulent mixing, and may be shallower or deeper than 200 m (*55*).
48. R. Reiter, *Phenomena in Atmospheric and Environmental Electricity* (Elsevier, Amsterdam, 1992).
49. B. A Tinsley, R. A. Heelis, *J. Geophys. Res.* **98**, 10375 (1993).
50. B. A. Tinsley, *Space Sci. Rev.* **94**, 231 (2000).
51. S. N. Tripathi, R. G. Harrison, *Atmos. Res.* **62**, 57 (2002).
52. B. A. Tinsley, R. P. Rohrbaugh, M. Hei, K. V. Beard, *J. Atmos. Sci.* **57**, 2118 (2000).
53. R. Markson, *Nature* **291**, 304 (1981).
54. R. G. Harrison, *Geophys. Res. Lett.*, in press; published online 16 July 2002 (10.1029/2002GL014878).
55. R. Reiter, *Phenomena in Atmospheric and Environmental Electricity* (Elsevier, Amsterdam, 1992).
56. M. Lockwood, *J. Geophys. Res.*, in press (10.1029/2002JA009431).
57. We thank M. Lockwood for drawing Fig. 2. This work was facilitated in part by the Philip Leverhulme Prize (to K.S.C.), for which we are grateful to the Leverhulme Trust.

**REVIEW** GEOPHYSICS

# The Spectral-Element Method, Beowulf Computing, and Global Seismology

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**The propagation of seismic waves through Earth can now be modeled accurately with the recently developed spectral-element method. This method takes into account heterogeneity in Earth models, such as three-dimensional variations of seismic wave velocity, density, and crustal thickness. The method is implemented on relatively inexpensive clusters of personal computers, so-called Beowulf machines. This combination of hardware and software enables us to simulate broadband seismograms without intrinsic restrictions on the level of heterogeneity or the frequency content.**

There has been tremendous growth in the acquisition of seismic data as a result of the deployment of digital broadband networks over the past two decades. This wealth of data has led to the construction of improved models of velocity heterogeneity, anisotropy, and attenuation in Earth. These models have provided important constraints on Earth's composition and physical processes (*1*–*3*). Nevertheless, improvements in seismic models will require the development, implementation, and application of methods that accurately incorporate the effects of mantle and crustal velocity and density heterogeneity on seismic wave propagation.

For one-dimensional (1D) Earth models that vary as a function of depth only, such as the Preliminary Reference Earth Model (PREM) (*4*) (Fig. 1A), semi-analytical techniques are widely used to calculate seismograms. Two popular methods are normal-mode summation (*5*), in which one sums spherical eigenfunctions, and the reflectivity method (*6*), in which the solution for a layered model is expressed as a sum in the frequency–wave number domain. To compute seismograms in three-dimensional (3D) Earth models, such as shear-velocity mod-

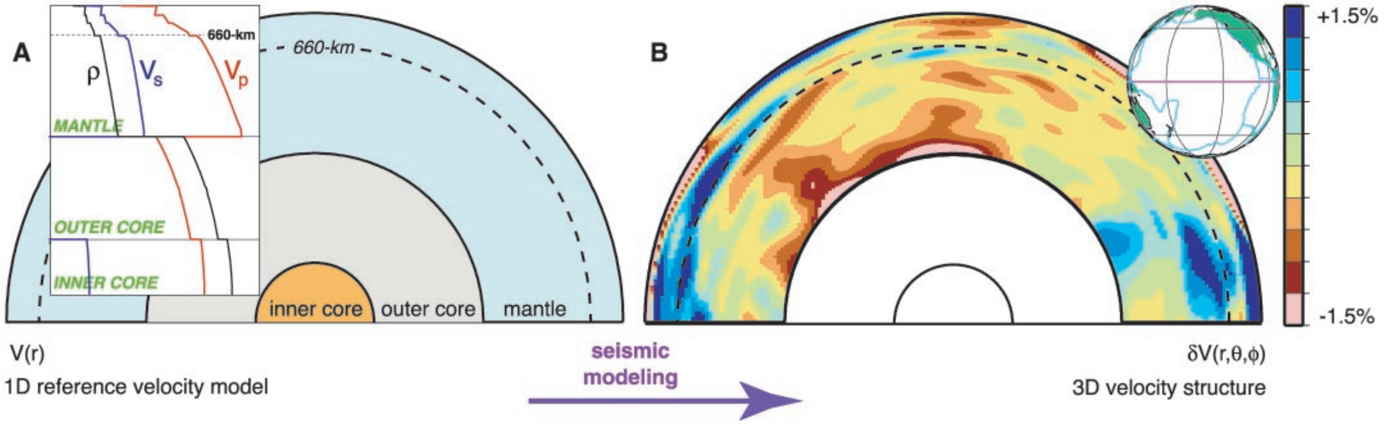

**Fig. 1.** Illustration of how seismic modeling is commonly conducted. (**A**) Cross section of Earth with the mantle, outer core, and inner core shaded blue, gray, and yellow, respectively. Superimposed on the left are 1D profiles of density ρ (black), shear velocity $V_s$ (blue), and compressional velocity $V_\rho$ (red) for PREM (*4*). The shear velocity is zero in the liquid outer core. Density and velocity vary smoothly throughout the model, except at compositional boundaries (e.g., the core-mantle boundary) or phase transitions in the upper mantle (e.g., at depths of 410 and 660 km). For 1D models such as PREM, which vary only as a function of depth, seismograms are computed using semi-analytical techniques such as normal-mode summation (*5*) or the reflectivity method (*6*). (**B**) Equatorial cross section through the Pacific mantle of shear velocity model S20RTS (*7*). Shown are relative lateral variations in shear velocity $\delta v(r,\theta,\phi)/v(r)$, where $r$ denotes the radius; θ, colatitude; and ϕ, longitude. These 3D variations are superimposed on the velocity $v(r)$ in the 1D reference model. Red colors denote lower than average velocity perturbations, and blue colors denote higher than average perturbations. For 3D models, seismologists commonly use asymptotic methods such as ray theory (*8*) or the path-average approximation (*9*) to construct seismograms.

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